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A national border-based assessment of Malawi's transboundary aquifer units: Towards achieving sustainable development goal 6.5.2

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ABSTRACT

Study region: Malawi.
Study focus: The adoption of the United Nations Sustainable Development Goal 6 in 2016 has triggered countries across the globe to assess and improve management and use of water resources. Monitoring of these resources is becoming increasingly important, and the management of transboundary water resources, in particular groundwater aquifers, required to meet SDG target 6.5.2, is lagging behind. It is vital to assess and manage these resources in a sustainable manner within an integrated water resource management approach. Transboundary aquifer assessments have largely focused on the regional scale which is not sufficient for countries to manage their transboundary aquifers effectively. This paper focuses on results of a national transboundary aquifer unit assessment in Malawi as a case study to support the countries plans for achieving Sustainable Development Goal 6.5.2.

New hydrological insights for the region: We have identified 38 new transboundary aquifer units shared between Malawi and its neighbours. These results can form the basis for future transboundary aquifer management between Malawi and its neighbouring countries. We also highlight the current limitations of transboundary aquifer assessments and management that should be addressed to achieve SDG 6.5.2. These include institutional mechanisms, limited cross-border data sharing, limited groundwater monitoring, and a need to revisit the wording of the transboundary-focused SDG target and its indicators.

1. Introduction

Over 783 million people across the globe do not have access to an improved source of drinking water, 40 % of which live in Sub-Saharan Africa (United Nations Department of Economic and Social Affairs (UNDESA, 2016). Sustainable development and management of this vital resource is essential as exemplified in the recent adoption of the Sustainable Development Goals (SDGs) by the United Nations in September 2015. Goal 6 of the SDG's is to ensure the availability and sustainable management of water and sanitation. Target 6.5.2 in particular recognizes the importance of integrated water resource management and furthermore, identifies that transboundary cooperation can play an important role in this (UN Water, 2015).

Transboundary aquifer's (TBA's) have long been known to store and transmit large volumes of groundwater from one country (or state) to another. It is important to identify those groundwater aquifers that may be transboundary in order to manage them

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effectively in conjunction with surface water within an IWRM framework. TBA assessments internationally have been largely focused on the regional scale (ILEC et al., 2016; Rivera and Candela, 2018). There are exceptions such as the Milk River Formation between Canada and the United States (Pétré et al., 2016, 2015), the Guarani Aquifer System, and the Ramotswa and Stampriet Aquifer Systems (de los Cobos, 2018; Nijsten et al., 2018a, b). The main driving force for international TBA assessments is the UNESCO-IHP (United Nations Educational, Scientific and Cultural Organization - International Hydrological Programme) through the Internationally Shared Aquifer Resources Management (ISARM) initiative and the International Groundwater Resources Assessment Centre (IGRAC). IGRAC publishes a 'Transboundary Aquifers of the World' map with all known TBAs displayed, based on the most recent inventory results from projects globally. This compilation of international data constitutes a valuable starting-point for governments. A large proportion of TBA's within Africa were identified through the 'Global Environment Facility Transboundary Waters Assessment Program' (GEF-TWAP) regional assessments (ILEC et al., 2016). The aim of the GEF-TWAP was to provide the first global scale assessment of transboundary waters. GEF-TWAP regional assessments were carried out by an appropriate representative from each country then collected and streamlined by the project.

It is estimated that 40 % of the world's population relies on transboundary groundwater as their primary drinking supply. Management, however, of TBA's, is still within its infancy both at a national and international level. Out of 678 TBA's identified worldwide, only 6 have an agreement governing their use and management (Rivera and Candela, 2018). Within Africa, the GEF-TWAP identified 80 TBA's. Of this 80, only 1 TBA has an agreement governing the use of it. Transboundary management is important in Africa as 75 % of the continent relies solely on groundwater as its primary water supply for agriculture, irrigation and drinking (Altchenko and Villholth, 2013). In order to manage these resources properly, sufficient transboundary aquifer assessments must be carried out. These often require substantial data sets and financial resources that are not always available to regions with low economic income, as is the case for a large proportion of Africa.

Fraser et al. (2018) advocates for countries to conduct a full national border based assessment of transboundary aquifers at both local and national scale in order to more directly apply transboundary associated sustainable integrated water resource management (IWRM). Within Malawi, a landlocked country in the south eastern region of Africa, there was a need to identify TBA units to support the government with water resource management while setting goals to achieve SDG 6.5.2. Malawi as a case study could be representative of other countries with similar financial circumstances or hydrogeology characteristics. With less than 1,400m3/year of available total renewable water resources per person (Fraser et al., 2018), Malawi is also one of the most water stressed countries in the world, more so than Botswana and Namibia, countries that contain large areas of desert within them. With its growing population of 2.9 % per year, climate change, and land degradation, the total available renewable water resources will decline further (Government of Malawi, 2018). By identifying all potential transboundary aquifer units that cross Malawi's international borders shared with Zambia, Tanzania and Mozambique, management strategies can be employed to target vulnerable areas and populations.

The understanding of Malawi's groundwater resources is still within its infancy. Although aquifer delineation has been conducted and productivity is well understood, specific characteristics including aquifer thickness, depth to water table, recharge and discharge zones, connectivity to surface waters, groundwater flow direction, groundwater contamination, natural groundwater quality etc. are either not reported or poorly understood to an appropriate level for sustainable management. This makes the challenge of identification and descriptions of transboundary aquifers even more challenging.

Moving forward on national based transboundary aquifer assessments, our work in evaluating the significance of local transboundary groundwater, seeks to account for the expected discontinuous nature of the basement complex arising from the complex comprising of multiple lithologies, and will consider the differences between the weathered and fractured zones within the basement complex to evaluate the significance of transboundary groundwater exchange (Fraser et al., 2018). Finally, a discussion of limitations to transboundary aquifer assessments both within the developing world context and internationally is presented. We highlight multiple challenges that must be addressed moving forward to achieve more reliable and detailed TBA assessments. The aims within the paper are thus to:

- Present the results of a national border based assessment of Malawi's transboundary aquifer units.
- Describe the identified transboundary aquifer units shared between Malawi and its neighbours alongside data gaps that will require addressing to move forward.
- Present a discussion of methodology limitations identifying issues such as cross border data harmonization and mapping consistency.
- Discuss the implication of these results within the SDG agenda

2. Methodology

The approach used for this study was to collect and synthesise all available literature and data relating to the transboundary aquifers shared between Malawi and its neighbours and to then create an initial interpretation of the TBA's along the entire Malawian national border that can provide a foundation for future more directed work. It is the first of its kind to assess transboundary aquifers across all of a countries international borders at one scale using the same method. Geological and hydrogeological maps have been used alongside literature and raw data in order to build a coherent picture of Malawi's transboundary aquifer situation. Building on the previous regional TBA assessment (IGRAC, 2015) through the TWAP, this study aims to provide a more detailed review of transboundary aquifers as a starting point for national scale and localised management. It is important to note this interpretation only accounts for land based aquifers and thus the potential transboundary aquifer units that reside partly under Lake Malawi have not been identified due to the lack of geological or hydrogeological data underneath Lake Malawi.

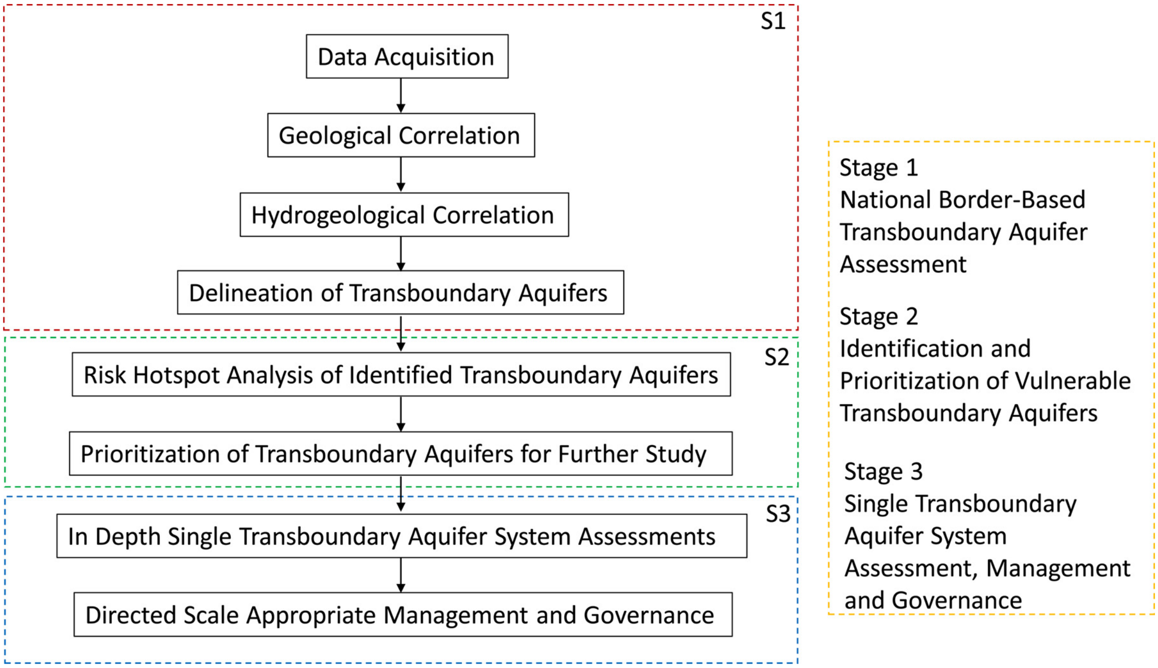

Fig. 1. Assessment framework for transboundary aquifers

Fig. 1 has been developed to underline the process of national border based transboundary aquifer assessments within an overall framework for assessing transboundary aquifers within a single country for multi-scale management. This study represents stage 1 of the process, with future research and work needed to complete stages 2 and 3.

2.1. Geological and hydrogeological correlation

The common hydrogeological principle that aquifers are defined by lithology changes was adopted. To interpret which aquifer units within Malawi crossed its international borders, Malawian geological maps (1: 250,000 scale, Geological Survey of Malawi, 1970) and hydrogeological maps (1: 250,000 scale, Government of Malawi, 1987) were georeferenced in QGIS and aligned with Mozambique hydrogeological maps (1:1,000000 scale, Ferro and Bouman, 1987a and b), Zambia geological and productivity maps (1: 1,000,000 scale, Geological Survey Department of Zambia, 1975; Deltares and Aurecon, 2016) and finally Tanzanian geological maps (1:125,000 scale, Geological Survey of Tanzania, 1953). Correlated geological lithological units between Malawi, Mozambique, Zambia and Tanzania are provided in supplementary material 1. Cross border geological harmonization although effective has some limitations and multiple assumptions were made in order to interpret the geological and hydrogeological data. Different methods of naming geological formations caused confusion and different scales of available data meant interpolation was required at some points. Although this methodology provides a starting point for resource limited countries to initially assess their TBA's, If TBA assessments are to improve and assist in the achievement of SDG 6, significant investment will have to be made in order to minimise the assumptions and limitations in future analysis.

To conduct the geological and hydrogeological harmonization effectively, multiple assumptions were needed and refining of these assumptions with further data would naturally allow for updated interpretation. The assumptions are:

- A water bearing geological unit as identified by any country, if transboundary, is assumed to also be water bearing in the neighbouring country and potential for cross border flow of groundwater.
- Where possible, the basement complex has been subdivided into different lithologies, however due to limited data in Zambia, this was not always possible. Where not possible, weathered/fractured basement units are separated in Malawi and assumed to continue into Zambia.
- Mineral composition of different basement complex units means they weather differently thus creating different aquifers properties.

2.2. Transboundary aquifer delineation

Known water bearing units were identified, and those that crossed Malawi's international border were assigned details of lithology, average yield and productivity. Where aquifer units crossed Malawi's border and matching geology and hydrogeology conditions within the neighbouring country existed, this was deemed to be a transboundary aquifer unit. Hydrogeological characteristics of each aquifer were then identified including lithology, surface area extent, productivity, potential surface water connections, water quality and finally, groundwater flow direction using piezometric surface maps.

2.3. Data gaps

Data gaps were noted upon identification and description of the transboundary aquifers. In many of the sparsely populated areas of Malawi and its neighbours, literature on groundwater quality and availability was limited. A lack of monitoring boreholes throughout Malawi and its neighbouring countries makes it difficult to establish if groundwater levels along the borders are depleting. Advancements in mapping and geological and hydrogeological understanding in Malawi may allow re-interpretation in support of SDG6.

3. Results

Results indicate that there is a total of 38 transboundary aquifer units shared between Malawi and its neighbours (Figs. 1 and 2). 26 of these TBA's are with Mozambique, 2 with Mozambique and Zambia, 4 with Zambia, 3 with Zambia and Tanzania and finally 3 with Tanzania. Malawi shares most of its transboundary aquifers with Mozambique and the least with Zambia. The aquifers hydrogeology ranges in productivity and the large majority of Malawi is covered in low yielding basement aquifers. There are however multiple smaller high yielding aquifers formed from alluvial and Karroo deposits that form productive and important local water sources.

3.1. Geological and hydrogeological correlation

The geology and hydrogeology of Malawi and its neighbouring countries has been previously described (Fraser et al., 2018; Smith-Carrington and Chilton, 1983; Upton et al., 2016). The TBA's range in lithology's encompassing Weathered Basement Complex, Fractured Basement Complex, the Karoo Sediments, the Karoo Basalts and Quaternary Alluvial Deposits (Fig. 2). As expected, the large majority of Malawi's aquifers are transboundary due to the small size of the landlocked nature of Malawi. A gap within central Malawi can be seen in Fig. 3 where there have been no identified TBA's as many of the aquifers within this area are small and localized and the little is known of the hydrogeology under Lake Malawi.

3.2. Transboundary aquifer unit descriptions

The identified transboundary aquifers are summarized in Table 1, separated by aquifer type and assigned a unique TBA number. Each aquifer type is described as follows.

3.2.1. Unconsolidated aquifers

The unconsolidated aquifers are composed of alluvial and colluvium lithologies. There are a total of 3 alluvial transboundary aquifers and 5 colluvial aquifers that extend across Malawi's borders (Fig. 2c). Often lying unconformably on top of other lithologies, these aquifers are the youngest within Malawi. The unconsolidated transboundary aquifers of Malawi are widespread across the country, most reside in the south of Malawi shared with Mozambique, and there is 1 colluvium aquifer shared in the central region with Zambia and another 2 in the north. These aquifers tend to be small compared to larger basement aquifers but are the most highly productive. Quaternary alluvial deposits are composed of clays, silts, sands and gravels, deposited in the floor of the East African Rift System (EARS) rift valley and along river plains (UN, 1989). The lithology of the deposits is highly variable (heterogeneous and anisotropic). The composition changes considerably over short distances due to the nature of their deposition from outwash fans, floor plains and river channels (Mkandawire, 2002). The mineral assemblages of these alluvium suggest that they are derived from the Precambrian Basement Complex, primarily from the gneiss (Habgood, 1963). The presence of clays meant that good yields with high water quality is only present within the gravel beds of the units where permeability was good (Habgood, 1963) and artesian water pressures may exist in places due confinement below clay layers. The depth of saturation within these aquifers varies seasonally. The water table depth is typically between 5 and 10 m below ground (Chavula et al., 2012) and thickness can range from 40 to 150 m (UN, 1989; Smith-Carrington and Chilton, 1983). The transmissivity ranges from 50 to 300 m^2/day, hydraulic conductivity for sands and gravels is between 10–20 m/day. Specific yield ranges between 3–10 % (Smith-Carrington and Chilton, 1983). The alluvial deposits are recharged through rainfall, which is spatially variable depending on location. Some additional recharge also comes from seepage of riverbeds that are permeable (Kelly et al., 2019b). These aquifers are unconfined when colluvium do not cover them.

Lying on alluvial deposits and weathered basement colluvium is also found. These are superficial deposits of residual soils formed by soil creep. These are commonly thin deposits, but are quite extensive across Malawi. Hydraulic conductivity for the poorly sorted clayley and colluvial sands ranges between 1–5 m/day with specific yield ranging between 3–10 % (Smith-Carrington and Chilton, 1983).

3.2.2. Karoo sequence

Within the western portion of the Shire River Basin in the southwest of the valley, a small section of Transboundary Karoo Sequence rocks exist. There are a total of 8 aquifers here composed of a combination of both basalts and sedimentary units (Fig. 2d).

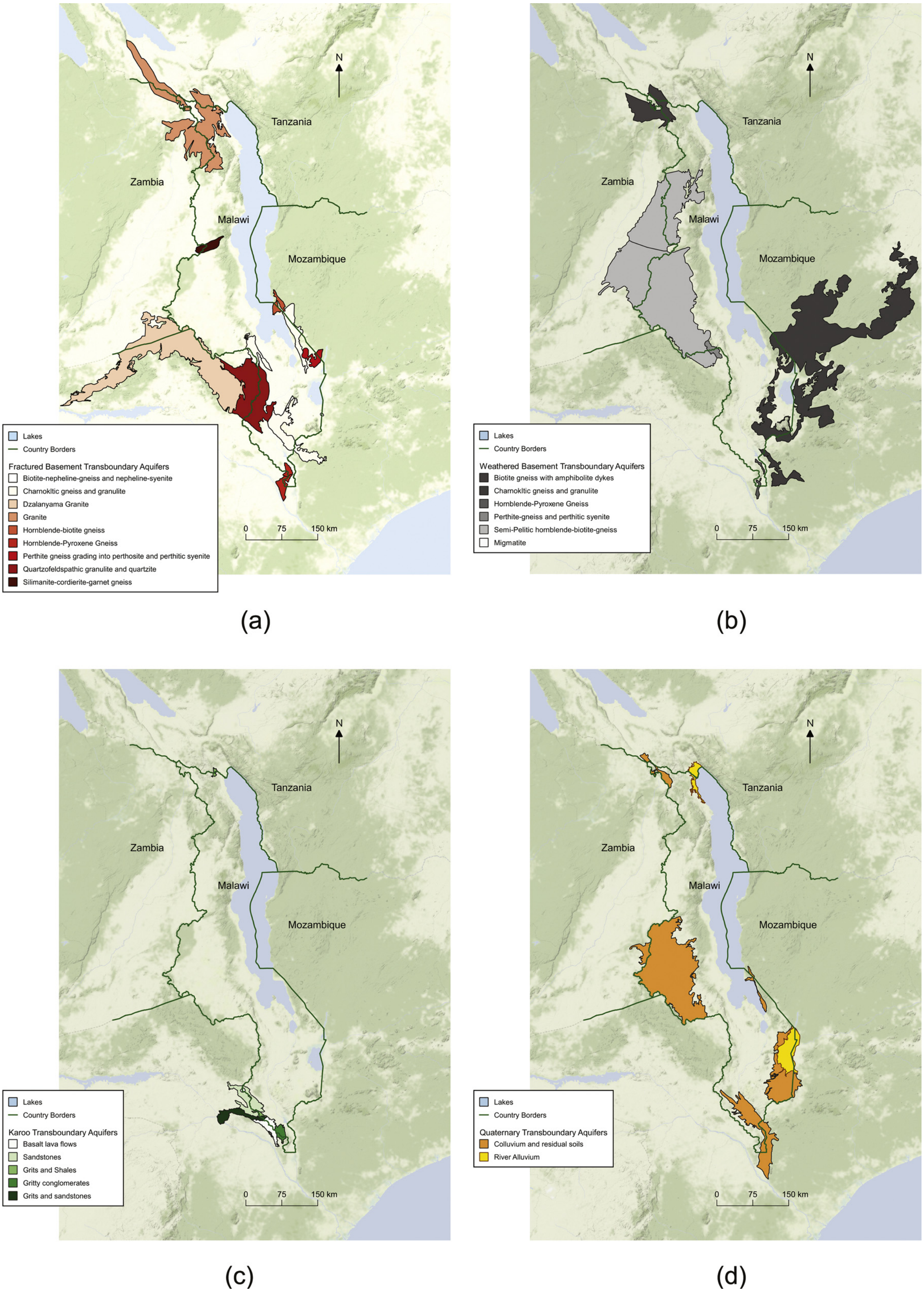

Fig. 2. (a), (b), (c) and (d) Transboundary Aquifers of Malawi, separated by lithology and type

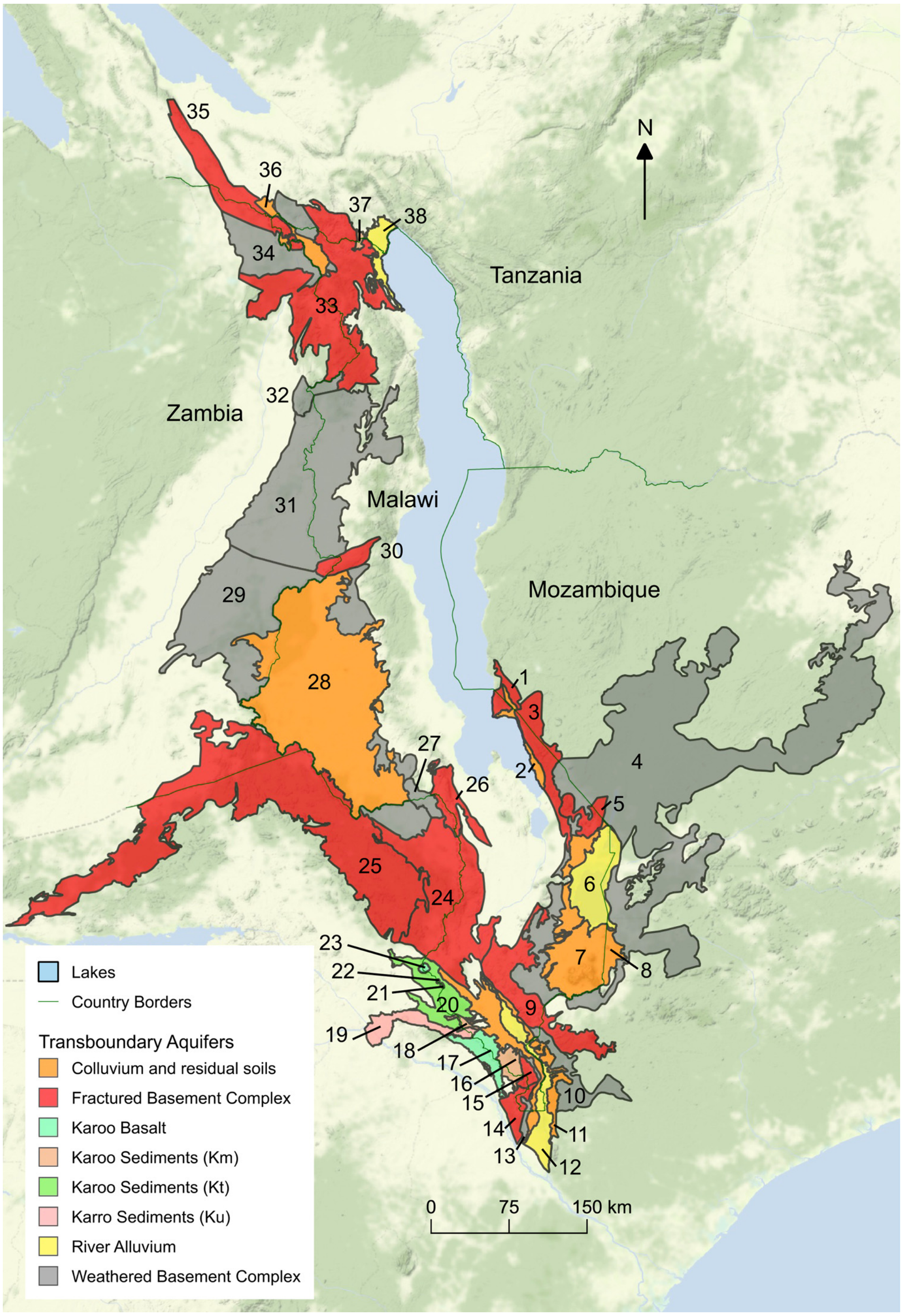

Fig. 3. Combined map of transboundary aquifers shared between Malawi and it neighbours (aquifers are numbered and linked to table 1)

Many of these aquifers are localised. They lie unconformably on crystalline basement and are fault bound on the Malawi side of the border due to the influence of the East African Rift System (Ferro and Bouman, 1987a). In the north, there is 1 other transboundary Karoo sedimentary aquifer shared with Tanzania.

The Karoo Stormberg Volcanics represent the upper part of the Karoo Sequence. They encompass a series of microporphyritic to glomeroporphyritic tholeiitic basaltic lava flows (Dill, 2007) often interbedded with bands of sandstone (Habgood, 1963). Permeable and porous layers exist between consecutive lava flows interbedded with layers of sandstone and tuff (UN, 1989). The flows are often vesiculated towards the top of top, and in-filled with calcite and quartz (Habgood, 1963). Within the centre of the Karoo weathered basalts, the unit is impermeable, however because of interstitial spaces at contacts between flow, there are zones where permeability

Table 1
Summary of each identified transboundary aquifers hydrogeological details (Kelly et al, 2019a; Kelly et al, 2019b; Bath, 1990; Chavula 2012; Smith-Carington and Chilton, 1983; Habgood, 1964; Bradford, 1973; UN, 1989; Mkandawire 2004)

TBA Number	Geological Lithology	Aquifer Type	Shared With	Surface Extent (km^2)	Aquifer productivity	Water Table Depth (m)	Surface Water Connections	Transmissivity (m^2/day)	Hydraulic Conductivity (m/d)	Groundwater Flow Direction	Other Information
1	Hornblende-biotite gneiss with graphite	Fractured Basement	Mozambique	628.2	Low to moderate	15 – 25	No Data	5 – 35	0.5 – 1.5	Mozambique to Malawi (northwest)	Extends up to and potentially into Lake Malawi
2	Colluvium and residual soils	Superficial	Mozambique	480.4	High to very high	5 – 10	No Data	50 – 300	1 – 10	Mozambique to Malawi (northwest)	Unconfined
3	Charnockitic gneiss and granulite	Fractured Basement	Mozambique	2082.7	Low to moderate	15 – 25	No Data	5 – 35	0.5 – 1.5	Mozambique to Malawi (northwest)	Groundwater of these aquifers tend to be of good quality
4	Charnockitic gneiss and granulite	Weathered Basement	Mozambique	37313.1	Low to moderate	15 – 25	Ruo River	5 – 35	0.5 – 1.5	Mozambique to Malawi (northwest)	
5	Perthite gneiss grading into perthosite and perthitic syenite	Fractured Basement	Mozambique	916.5	Low to moderate	15 – 25	No Data	5 – 35	0.5 – 1.5	Mozambique to Malawi (northwest)	
6	River alluvium	Superficial	Mozambique	2853	High to very high	5 – 10	No Data	50 – 300	1 – 10	Malawi to Mozambique (east)	Alluvial aquifers can exhibit high chloride salinity levels due to mineralization
7	Colluvium and residual soils	Superficial	Mozambique	7791.2	High to very high	5 – 10	Ruo River	50 – 300	1 – 10	Malawi to Mozambique (east)	
8	Nepheline-syenite	Fractured Basement	Mozambique	31.6	Low to moderate	15 – 25	No Data	5 – 35	0.5 – 1.5	Malawi to Mozambique (east)	
9	Charnockitic gneiss and granulite	Fractured Basement	Mozambique	3849.2	Low to moderate	15 – 25	No Data	5 – 35	0.5 – 1.5	Malawi to Mozambique (south)	
10	Charnockitic gneiss and granulite	Weathered Basement	Mozambique	1784.1	Low to moderate	15 – 30	No Data	5 – 35	0.5 – 1.5	Malawi to Mozambique (south)	High fluoride and Iron content in groundwater
11	Colluvium and residual soil	Superficial	Mozambique	4966.6	High to very high	5 – 10	No Data	50 – 300	1 – 10	Malawi to Mozambique (south)	
12	River alluvium	Superficial	Mozambique	1930.3	High to very high	5 – 10	Shire River and tributaries	50 – 300	1 – 10	Malawi to Mozambique (south)	Recharge in east of aquifer more than 2000 mm/yr. High Fluoride, and chloride salinity in lower Shire.
13	Hornblende-pyroxene-gneiss	Weathered Basement	Mozambique	228.5	Low to moderate	15 – 30	No Data	5 – 35	0.5 – 1.5	Malawi to Mozambique (south)	
14	Hornblende-pyroxene-gneiss	Fractured Basement	Mozambique	774.8	Low to moderate	15 – 25	No Data	5 – 35	0.5 – 1.5	Malawi to Mozambique (south)	

(*continued on next page*)

Table 1 (*continued*)

TBA Number	Geological Lithology	Aquifer Type	Shared With	Surface Extent (km^2)	Aquifer productivity	Water Table Depth (m)	Surface Water Connections	Transmissivity (m^2/day)	Hydraulic Conductivity (m/d)	Groundwater Flow Direction	Other Information
15	Hornblende-pyroxene-gneiss (partly garentiferous)	Fractured Basement	Mozambique	332.7	Low to moderate	15 – 25	No Data	5 – 35	0.5 – 1.5	Malawi to Mozambique (south)	
16	Mwanza gritty conglomerates	Karoo Sediments (Km)	Mozambique	576.4	Low to moderate	20 – 30	No Data	No data	No data	Malawi to Mozambique (south)	
17	Basalt lava flow	Karoo Basalt	Mozambique	1065.7	Moderate	Unknown	No Data	No data	No data	Malawi to Mozambique (south)	Fault bound on the Malawi side. Intrudes through the Karoo Sediments
18	Mwanza grits and shales	Karoo Sediments (Km)	Mozambique	134.2	Low to moderate	20 – 30	No Data	No data	No data	Malawi to Mozambique (south)	
19	Upper sandstones (grits and sandstones)	Karoo Sediments (Ku)	Mozambique	1283.4	Low to moderate	20 – 30	No Data	No data	No data	Malawi to Mozambique (south)	
20	Lower sandstones	Karoo Sediments (Kt)	Mozambique	2283.8	Low to moderate	20 – 30	No Data	No data	No data	Malawi to Mozambique (south)	Oldest Karoo Sediments. Potential for deep fossil aquifers.
21	Mwanza grits and shales	Karoo Sediments (Km)	Mozambique	11.4	Low to moderate	20 – 30	No Data	No data	No data	Malawi to Mozambique (south)	Karoo aquifers tend to be fairly unexplored in this region
22	Mwanza grits and shales	Karoo Sediments (Km)	Mozambique	8.4	Low to moderate	20 – 30	No Data	No data	No data	Malawi to Mozambique (south)	
23	Basalt lava flow	Karoo Basalt	Mozambique	67.3	Moderate	Unknown	No Data	No data	No data	Malawi to Mozambique (south)	
24	Quartzofeldspathic granulite and quartzite	Fractured Basement	Mozambique	8616.7	Low to moderate	15 – 25	No Data	5 – 35	0.5 – 1.5	Mozambique to Malawi (southeast)	
25	Granite (dzalanyama)	Fractured Basement	Mozambique and Zambia	21136.3	Low to moderate	15 – 25	No Data	5 – 35	0.5 – 1.5	From Zambia and Malawi to Mozambique (southeast)	
26	Charnockitic gneiss and granulite	Fractured Basement	Mozambique	1478.9	Low to moderate	15 – 25	No Data	5 – 35	0.5 – 1.5	Mozambique to Malawi (east)	High sulphate in Salima sub catchment, caused by gypsum saturation
27	Perthite-gneiss and perthitic syenite	Weathered Basement	Mozambique	595.0	Low to moderate	15 – 25	No Data	5 – 35	0.5 – 1.5	Mozambique to Malawi (east)	
28	Colluvium and residual soils	Superficial	Zambia	18815.3	High to very high	5 – 10	Bua Catchment	50 – 300	1 – 10	Zambia to Malawi (east)	Iron problem in weathered basement complex in Bua Catchment of up to 59 mg/l
29	Biotite-gneiss with garnet in parts	Weathered Basement	Mozambique and Zambia	31640.7	Low to moderate	15 – 25	No Data	5 – 35	0.5 – 1.5	Zambia to Malawi (east)	

(*continued on next page*)

Table 1 (*continued*)

TBA Number	Geological Lithology	Aquifer Type	Shared With	Surface Extent (km^2)	Aquifer productivity	Water Table Depth (m)	Surface Water Connections	Transmissivity (m^2/day)	Hydraulic Conductivity (m/d)	Groundwater Flow Direction	Other Information
30	Silimanite-cordierite-garnet gneiss	Fractured Basement	Zambia	891.2	Low to moderate	15 – 25	No Data	5 – 35	0.5 – 1.5	Zambia to Malawi (east)	
31	Semi-pelitic hornblende-biotite-gneiss	Weathered Basement	Zambia	14089.0	Low to moderate	15 – 25	No Data	5 – 35	0.5 – 1.5	Zambia to Malawi (east)	High chloride salinity recorded up to 2000 mg/l in South Rukuru
32	Magmatite	Weathered Basement	Zambia	816.4	Low to moderate	15 – 25	No Data	5 – 35	0.5 – 1.5	Zambia to Malawi (east)	
33	Granite	Fractured Basement	Zambia and Tanzania	13621.3	Low to moderate	15 – 25	No Data	5 – 35	0.5 – 1.5	Mozambique to Malawi (east)	
34	Biotite gneiss with amphibiotite dykes	Weathered Basement	Zambia and Tanzania	4476.0	Low to moderate	15 – 25	No Data	5 – 35	0.5 – 1.5	Zambia to Malawi (east)	
35	Granite	Fractured Basement	Zambia and Tanzania	13621.3	Low to moderate	15 – 25	No Data	5 – 35	0.5 – 1.5	Runs along border to the east	
36	Colluvium and residual soils	Superficial	Tanzania	883.9	High to very high	5 – 10	No Data	50 – 300	1 – 10	Runs along border to the east	
37	Mwanza grits and shales	Karoo Sediments (Km)	Tanzania	113.5	Low to moderate	20 – 30	No Data	No data	No data	Runs along border to the east	
38	River alluvium	Superficial	Tanzania	34.0	High to very high	5 – 10	No Data	50 – 300	1 – 10	Malawi to Tanzania (east)	Extends up to and potentially into Lake Malawi

is very high. This is due to vesicular cavities providing a flow path for the water (Habgood, 1964). Furthermore, jointing and faulting of the lava flows has resulted in fracturing that increases permeability further. Groundwater movement through the basalts is fairly rapid as illustrated through the high quality and low mineralization of the water with yields, above 1.1 l/s (Habgood, 1964). These may form moderate productivity local aquifers.

The Karoo sedimentary rocks can be subdivided into three distinct units; The basal beds composed of conglomerates and sandstones; a sequence of sandstones, mudstones, shales and coal seams in the middle; and grits, arkose sandstones, shales, mudstones and marls in the upper section. The upper successions tend to be cemented by calcite and the primary porosity is low. Permeable horizons are related to secondary fracturing. The Karoo Sediments are thought to have an estimated thickness of 500 m (Bradford, 1973; UN, 1989).

The Karoo sedimentary rock outcrops tend to be relatively small and not vastly abundant. Despite this the units tend to exhibit high permeability and tends to be highly fractured. The rocks of the Karoo are generally well-cemented with low porosity and intergranular permeability. Groundwater storage and flow occurs largely in fractures in the rocks. Groundwater levels are typically 20 m–30 m below ground surface (UN, 1989). These rocks may form a low to moderate productivity local aquifer. The groundwater quality of the Karoo sediments tends to be highly variable depending on location and depth ranging from freshwater to extremely saline water. Within the south of Malawi, the Karoo aquifers tend to be either dominated by calcium carbonate or sodium chloride influenced water types.

3.2.3. Fractured basement complex

There are 13 unique sub-sets of fractured basement complex transboundary aquifers identified within this study. They extend across the entire of Malawi predominantly in the center of the country along the border shared with Zambia and along the southeast border shared with Mozambique (Fig. 2a).

Precambrian crystalline basement rocks are gneiss and granulite with some metamorphic schists, quartzites and marbles (UN, 1989). The basement complex is intruded by dykes and other igneous lithologies. (UN, 1989). The large majority of Malawi is underlain by these rock units that have undergone several deformation and metamorphic phases that has affected large areas of Africa (Cannon et al., 1969). Due to their resistance to erosion they often form much of the elevated regions in Malawi. In the north and west of Malawi, the basement complex exists as lower grade metamorphic rocks, those in the south were originally mudstone, sandstone and conglomerates. It is most likely that these rocks are from a sedimentary origin pre metamorphism (Bloomfield, 1968). Due to recrystallization during deformation, the basement rocks have been rendered with both low primary porosity and permeability.

The fractured basement complex aquifers store groundwater in fractures (secondary porosity) associated with geologically weak zones, easily disintegrated into individual blocks, bounded by fractures and joints (Fraser et al., 2018). These zones are associated with particular geological structures like folds, faults and fractures displaying relatively high permeability. Along dikes intruding the basement complex, aquifers can also develop in the fracture zone on the contact between the intrusive body and the adjacent rocks. The un-fractured parts of the dikes often form impermeable barriers (Ferro and Bouman, 1987a, b).

It is probable that the basement complex aquifers provide baseflow for many of the country's surface watercourses and despite the semi-confined nature of the surface clays, recharge is most likely to come in the form of rainfall infiltration (Kelly et al., 2019a, b; Smith-Carrington and Chilton, 1983). Conductivity borehole logging and analysis of boreholes tapping the basement complex aquifer suggests water quality layering within the units. Distinct layering with considerable lateral variation is evident suggesting that there may be more than one water type within some aquifers. Furthermore, in some localized areas, there is evidence of mixing of these different water types (Smith-Carrington and Chilton, 1983).

These units tend to yield 0.5 − 0.8 l/s from around 30 − 45 m depths. This is often enough to supply local villages but not regional areas (Habgood, 1964). The water acquired is of good quality with low salinity. Often, these aquifer units are not reached when drilling due to being too deep resulting in high expense (Habgood, 1964; Kalin et al., 2019). Locally, some parts of the aquifer units do tend to exhibit saline water, this does not appear to be related to the rock composition and is more likely caused by evaporation and mineralization along fault zones (Rivett et al., 2018). Overall, the units do tend to exhibit low mineralization regionally and this suggests that recharge is recent.

Fractured basement complex lithology's are discontinuous resulting in local aquifers as opposed to large scale regional aquifers (Fraser et al., 2018). Although low yielding, these aquifers are often an important local groundwater resource and therefore must be considered locally within the context of Sustainable Development Goal 6.

3.2.4. Weathered basement complex

There are 8 weathered basement complex aquifers shared between Malawi and its neighbours. These saprolitic units range in size from smaller more local scale aquifers in the very south and north of Malawi to larger more regionally significant aquifers in the south east (Fig. 2b). Formed of the same geological lithologies as the fractured basement aquifers, the weathered aquifers differ in the type of secondary saprolitic porosity exhibited to store water. The process of weather involves the breakdown of the bedrock through chemical and physical factors. The occurrence of coarse grained or heterogeneous rocks as well as soluble marbles, or the existence of contacts between rock types of different nature also facilitate weathering. The weathered basement aquifers are best developed in topographical highs within Malawi (Smith-Carrington and Chilton, 1983). It can be divided into 3 distinctive layers: the laterite layer which is composed of mainly red clay or completely weathered silt; the saprolite layer which is composed of quartzitic clayey sand or heavily weathered fine to coarse sand; and medium weathered layer in which rock mass is separated into fragments or small blocks by groundwater infiltrating into joints of rock (Zauyah et al., 2010; Smith-Carrington and Chilton, 1983). The best yielding layer is the medium saprolite layer and it occurs between 15 – 30 m. The aquifer thickness or the occurrence depth is very variable due to topographic conditions. Weathering is controlled by the rock type and structure, slope, regional climate, lithology and mineral type, the spacing between joints and the degree of rock mass (Spellman and Stoudt, 2013; Smith-Carrington and Chilton, 1983; UN, 1989). As an example, gneiss and granulites are coarse grained with quartz minerals. Weathering of these units provides a good water bearing capacity. Schist, syenite and gabbro on the other hand exhibit clay minerals and poor water bearing capacities (Smith-Carrington and Chilton, 1983). Weathered basement aquifer transmissivities are generally in the range of 5 to 35 m^2/day with estimated hydraulic conductivities ranging from 0.01 to 1 m/d. The storage coefficient, on the other hand, has been assumed to range from 0.01 to 0.001 (Mkandawire, 2004). These aquifers are under unconfined to confined conditions. Borehole yields are generally highest where the saturated thickness of the weathered zone is greatest and the parent bedrock coarsest (Chilton and Smith-Carington, 1984). In general, the weathered basement aquifer produces low borehole yields (Chilton and Smith-Carington, 1984).

3.3. Data gaps

Although the basic hydrogeological characteristics of the transboundary aquifers are understood (Table 1), a number of data gaps have been highlighted throughout this study. The lack of monitoring boreholes in place to monitor groundwater levels means that potential groundwater depletion within these aquifers is unknown. This makes it difficult to determine whether a transboundary aquifer is under stress or at risk of abstraction becoming unsustainable. There is also limited data available on the use of groundwater. Although it is well established that a large proportion of Malawi's rural communities rely on groundwater as their primary drinking water source, other uses of groundwater are poorly understood. Other vital information such as recharge and discharge zones of these transboundary aquifers are inadequately investigated. This will pose problems if Malawi and a neighbouring country were to want to foster an agreement over one of their shared aquifers as international recharge and discharge can play an important role in the conceptualisation of a transboundary aquifer and will direct the appropriate legal frameworks required to direct the aquifer agreement. Within Malawi, some studies have been done looking at the hydraulic connections that exist between groundwater and surface water however these are still in their infancy and still require further attention. Furthermore, evidence of groundwater contamination within these aquifers is only viable for those aquifers that have been tested; the assumption that no record of contamination means no contamination should not be taken.

Within Malawi there is also a north-south divide on the amount of research and field investigations done to assess and understand groundwater resources. The center and south of Malawi is more densely populated than the north and this has contributed to the majority of research funding being directed in these areas. The Shire River Valley and its related river basins, aquifers and catchments are also an important water and energy supply in the region that has subsequently led to a focus on this area for research. The lack of data in the North of Malawi in relation to the south has resulted in a diminished understanding of the water resources in the North, which contributes to the shortage of transboundary understanding.

4. Discussion

The results of this study indicate that there are many more small-scale transboundary aquifers in Malawi, and likely across Africa than previously thought. This is important as current management structures in place within these countries often do not facilitate local scale transboundary management. Studies of this scale are also hindered by multiple limitations. Data availability is a major issue in many countries and this case study is not exempt as previously discussed. Alongside this, the detail of geological and hydrogeological maps that require harmonization across the border at this scale is much more complex resulting in increased difficulty in interpretation of aquifer units. Additionally, mapping consistence and different approaches to lithology delineation complicates harmonization further.

The importance of transboundary water management has been recognised within the Sustainable Development Goal agenda. Target 6.5.2 specifically refers to transboundary water; "by 2030, implement integrated water resources management at all levels, including through transboundary cooperation as appropriate" (UN Water, 2015). The nature of integrated water resource management demands both surface and groundwater to be considered in a holistic management approach (UN Water, 2017b). Historically the management of surface water has received comparatively more attention than groundwater (Eckstein and Sindico, 2014). This could be due to the simplicity in determining whether a lake or river crosses a political boundary, and the complexity of detailed study of hydrogeological units and groundwater flow. It is important to identify those groundwater aquifers that may be transboundary in order to manage them effectively in conjunction with surface water within an IWRM framework.

It can be argued the current SDG agenda for transboundary groundwater management is premature. This study alone shows that transboundary aquifers are still not understood at an effective level of detail for local management and national agreements. The expectation on countries to not only investigate, identify and establish a formal agreement over the use and management of these aquifers by 2030 appear to be a stretched target, especially given that only 6 formal agreements are currently in place over transboundary aquifers (Rivera and Candela, 2018). There is an inherent risk the SDG agenda will rush the transboundary aquifer identification process up and detail is missed. If detailed transboundary aquifer assessments like the one in this study are not undertaken, generalized regional assessments will be relied upon that may not be fit for purpose.

A key objective of the SDG's is 'Leave no one Behind', and therefore the localization of the policy and management of resources in line with SDG's must be a corner stone of national implementation strategy (United National Committee for Development Policy (UNCDP, 2018). Relying on generalized regional groundwater assessments will lead to poor or miss-management of the groundwater that are highly important at the local level. Transboundary aquifer assessments are also still restricted by data limitations, lack of cross-bored data sharing, harmonizing cross border hydrogeological data, and limited groundwater monitoring practices (Fraser et al., 2018). Additionally, developing countries are faced with financial and capacity limitations that require national prioritisation under the SDG's which further inhibits TBA agreement development.

The wording of SDG target 6.5.2 leaves potential for gaps in the interpretation. The target calls for transboundary cooperation within Integrated water resource management at all levels as appropriate however the indicator for the target only measures the proportion of transboundary basin area with an operational agreement (McCracken and Meyer, 2018). Firstly, groundwater aquifers do not necessarily follow surface water river basins and therefore the target has failed to identify this key differential (Fraser et al., 2018). Primarily focusing on the surface river basin level diminishes the importance of local cooperation of groundwater use by a substantial percentage of the population base. There is no guidance over what constitutes the need for transboundary cooperation within the SDG agenda and if there was, it would likely focus on reactive measures than proactive as integrated water resource management promotes reactive measures to water conflict instead of focusing on preventative approaches (Jarvis, 2010). Furthermore, some aquifers or indeed large areas of aquifers may not require an agreement over their use and management due to lack of usage or low dependency rates (Fraser et al., 2018).

The SGD 6.5 target indicator calls for the percentage of a basin under an operational agreement to be calculated. The term 'operational' requires any arrangement to include regular exchange of data, regular formal communication between parties, a joint management plan, and a joint body or mechanism to oversee the arrangement (UN Water, 2017a in McCracken and Meyer, 2018). Operational agreements of this manner and at this scale will require strong governance and institutions to implement them. Aligning the SGD's indicators with already in-place institutional mechanisms will speed up this process. However there are relatively few institutional mechanisms designed to manage transboundary groundwater resources. Often, these tools generally exist at the sub-national level (Linton and Brooks, 2011; Feitelson, 2003 in Ganoulis and Fried, 2018). In order to be effective, cooperation needs to happen at all scales. (UNESCO, 2016). Most examples of transboundary institutional mechanisms come in the form of joint bodies/commissions/committees created for river basin based cooperation. Case studies include (1) the International Commission on the Scheldt River that was set up to strengthen transboundary cooperation over the quality of the Scheldt River Basin District that runs through France, Brussels and the Netherlands (Machard de Gramont et al., 2001), (2) the Nile Basin Initiative that brings member states residing within the basin together for consultation and coordination of sustainable management and development of shared water within the basin (UN and UNESCO, 2018) (3) the Okavango River Basin Water Commission that established the Okavango Delta Management Plan through engaging with stakeholders such as communities of the delta, users of the resource, governments and management institutions (UN and UNESCO, 2018) (4) the Orange-Senqu River Commission formed following signing the 'Agreement for the Establishment of the Orange-Senqu River Commission' between Botswana, Lesotho, Namibia and South Africa established to promote equitable and sustainable development of the resources of the Orange-Senqu River basin, including groundwater by proxy (UNESCO-IHP, 2016) (5) the North-South Ministerial Council that was formed as a response to the Belfast Agreement fostered between Northern Ireland and The Republic of Ireland that encourages cross-border cooperation between the two nations, including over shared water recourses (Fraser et al., 2020). A common factor that is evident is that most institutional mechanisms that deal with transboundary groundwater governance are at the River Basin level, and have been initially driven by the desire for surface water management, with groundwater included as an addition. It is also often unclear within these mandates whether or not groundwater within the basin limits but not hydraulically connected to the surface waters are included (UNESCO-IHP, 2016).

Specific examples of effective institutional governance mechanisms dealing with just groundwater have developed as a consequence of international scale projects such as the 'Governance for Groundwater Resources in Transboundary Aquifers (GGRETA)' Project developing tools such as Multi-Country Cooperation Mechanisms (MCCM); a dedicated instrument to deal with transboundary groundwater management that can be nested within another institution. In GGRETA's case, within the Orange-Senqu River Commission (UNESCO-IHP, 2016). Similarly, the RAMOTSWA and Shire CONWAT project both utilize Joint strategic action plans to identify and prioritize investment and actions that can be implemented for transboundary groundwater management with their respective regions (SADC-GMI, 2016; IWMI, 2019).

More pertinent to the Malawi case study, the Southern African Development Community (SADC) has been progressive with its stance on transboundary water cooperation through its Water Division by developing a Regional Water Strategy that provides a strategic framework for sustainable use, protection and control of both national and transboundary water resources within the region, and the implementation of the Revised Protocol for Shared Watercourses (2000) that aims to foster close cooperation between member states over their shared water resources (SADC, 2003). Most recently, the SADC-Groundwater Management Institute, a not-for-profit based in South Africa representing all SADC member states, was established to promote sustainable groundwater management within the region, build national and regional institutional capacity, lead national and regional coordination and improve knowledge management. A large part of its work is transboundary focused (SADC-GMI, 2016; IWMI, 2019).

93.2 % of Malawi's territorial area and 86.1 % of its population (Republic of Malawi Ministry of Agriculture, Irrigation and Water Development (MoAIWD, 2014) resides within the Zambezi River Basin and is party to the ZAMCOM Agreement; an agreement that sets out to foster cooperation from riparian states over the transboundary management of the surface water and groundwater within the basin (SADC-DW/ Zambezi River Authority, 2008). Moving forward, an option for this commission may be to set up a hydrogeological working group that can represent transboundary groundwater issues at the international level. An effective working example of this is the ORASECOM hydrological group within the commission (Nijsten et al., 2018a, b). Although almost all of their transboundary aquifers reside within this transboundary basin, Malawi is yet to accede the ZAMCOM agreement into policy (ZAMCOM, 2019). It must do so in order to move forward with transboundary cooperation at the binational level.

These institutional frameworks discussed must be underpinned by local scale mechanisms. Local stakeholder involvement and local scale governance mechanisms are vital as those involved are often closest to the problem at hand and most impacted by poor resourse management (Moench et al., 2012). The most common local-scale water governance mechanism is 'Community Based Management' (CBM) (Whaley et al., 2019). The CBM model is based on the concept of the local community managing their own water resources, often through the maintenance of water points such as hand-pumped boreholes. CBM WAS initially intended to provide a sense of ownership through local participation through Water Point Committees (Benito et al., 2010) and account for decentralized governmental systems in many areas of Africa (Truselove et al., 2019). However, research has suggested that the burden and services contained within CMB cannot be sustained long-term and that there is an issue of meeting the SDG's and sustainable financing for maintenance under a CBM approach (Truselove et al., 2019, 2020). Community based management is also rarely seen at the formal transboundary level. Any transboundary cooperation is often informal and thus unrecorded and rendered ineffectual for the SDG mandate.

As previously noted, many of Malawi's transboundary aquifers are localised and therefore generalised policies at international basin level are not appropriate. In these cases, national policy that supports local level IWRM management strategies would be more effective. Moving forward, it may also be practical to identify particular vulnerable areas of transboundary aquifers that require management, rather than choosing to manage an entire aquifer. SDG 6.5.2 will require a formal agreement, and it is vital these recognise local dependence and vulnerabilities, without the approach presented here, generalised transboundary agreements will likely hinder local level development progress.

5. Conclusions and the way forward

The adoption of the Sustainable Development Goals has driven forward the importance of localisation of policy, planning, and management, and for goal 6, the need for sustainable and integrated transboundary aquifer management. This paper presents an approach to transboundary aquifer assessment at local level that supports Malawi (as a case study) and other countries to assess their border for transboundary aquifers shared with neighbours. It relies on the use of detailed geological and hydrogeological data alongside literature and groundwater studies. In Malawi, 38 transboundary aquifers of local to national importance were identified as being shared between Malawi and its neighbouring countries, an increase from the previous 3 identified, demonstrating the complexity lost in regional scale assessments. These aquifers vary in lithology, productivity and extent across the country, but all are locally important for water access to rural populations, local agriculture, and sustainable water resources. The assessment took into account the discontinuous nature of the basement complex arising from the complex comprising of multiple lithologies, and the differences between the weathered and fractured zones within the basement complex. These results form the basis for future transboundary aquifer studies, and discussions around management and agreement between Malawi and its neighbouring countries to set targets to achieve SDG 6.

Moving forward, it will be important to ensure that local-level transboundary aquifer assessments inform SDG 6.5.2. It will also be essential to ensure that specific vulnerable areas or ecosystems, or populations using these aquifers, are identified, monitored, and managed effectively. This could be in the form of zoning or potentially geospatial GIS hotspot analysis. It will also be important to consider that large scale aquifers likely have smaller areas of concern that require management and that these are likely to reside close to the border and have a community level impact. Engaging these stakeholders and building capacity in these areas will be essential for local scale management.

CRediT authorship contribution statement

Christina M. Fraser: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Writing - original draft, Writing - review & editing. **Robert M. Kalin:** Conceptualization, Data curation, Funding acquisition, Supervision, Writing - review & editing. **Modesta Kanjaye:** Data curation, Resources, Validation, Writing - review & editing. **Zione Uka:** Data curation, Resources, Validation, Writing - review & editing.

Declaration of Competing Interest

The authors report no declarations of interest.

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Appendix A. Supplementary data

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